

Degradation of Structure Strength by Welding Heat Effect for Hot-stamped Material

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ABSTRACT

The phenomenon where welding heat reduces the structure strength performance of hot-stamped materials used in automobile bodies was clarified. Tests using test pieces demonstrated that continuous welding methods, such as laser welding, that transmit heat over a wide range may reduce the structure strength performance compared to resistance spot welding. CAE analysis was performed to clarify the mechanism of this phenomenon. The material strength properties were obtained using micro tensile test specimens and applied to CAE models to reproduce the phenomenon where welding heat softens the area around the weld. The calculation results closely matched the test results, which showed that the drop in structure strength performance is due to material softening. In addition, the relationship between the material softening range and structure strength performance was investigated, and showed that softening of the welding flange area has a small effect, and softening of the hinge line areas has a large effect. This is because the hinge line areas bear a large share of the structural stress, and softening occurred in these areas. These results provided useful knowledge for future investigation of body structures and welding methods.

1. Introduction

High-tensile steel is increasingly used in automobile bodies to help secure strength for better crash safety performance and to reduce weight for better fuel efficiency performance. In particular, use of hot-stamped steel sheet materials with high tensile strength continues to expand rapidly^{(1), (2)}. The hot stamping method heats special steel sheets to approximately 900°C and then presses the sheets while at the same time rapidly cooling them with the die to achieve a tensile strength of 1500 MPa or more. Parts made by this method are used in many body frame members such as the front pillar, center pillar, and side sill to reduce cabin deformation and protect passengers in the event of a crash (Fig. 1)⁽¹⁾.

Meanwhile, there are reports that for high-tensile steel with strength in excess of around 780 MPa, welding heat softens the materials around the weld, reducing the weld strength⁽³⁾⁻⁽⁵⁾. Continuous welding, such as laser welding, is increasingly used to enhance body stiffness and crash safety performance⁽⁶⁾. Continuous welding transmits heat over a wide range, so it is thought that heat-induced softening will occur over a wider range when compared to resistance spot welding (RSW), which is

widely used in vehicle bodies. However, there are no reports known to date of this heat reducing the structure strength performance. Body structure strength is a key factor for body performance, so it is necessary to clarify this phenomenon and apply the knowledge to future development.

This study manufactured test pieces using hot-stamped materials welded by RSW, laser welding, and other methods, and then performed bending tests to clarify the

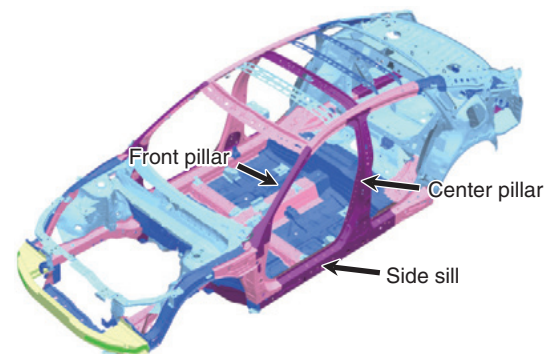


Fig. 1 Applicable parts made of hot-stamped material

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effects on strength performance. CAE was also used to model the micro strength properties of softening locations near welds to investigate factors reducing the strength. In addition, the relationship between the softening range and structure strength performance was clarified, locations exhibiting large drops in performance were identified, and these results were verified by tests using actual parts.

2. Clarification of Softening and Effect on Structure Strength Performance

Tests were performed using test pieces that simulate the frame to clarify the effect of welding heat on body strength performance. Parts that use hot-stamped materials are often used in body locations where bending deformation occurs in crashes. For this reason, evaluation was performed by bending tests.

2.1. Test Method

The test piece shape used a structure with two hat shapes stacked and welded together (hereafter, hat part) to simulate a typical center pillar section (Fig. 2). The materials were aluminum-plated steel for hot stamping, and Table 1 shows the mechanical properties after hot stamping. The thickness was 1.6 mm and the length was 1,000 mm. The flat part of the welding flange had a width of 16 mm.

Figure 3 shows each welding method. The three typical continuous welding methods of laser welding, arc welding, and seam welding were used. Comparison was performed using the commonly used 30 mm pitch RSW (hereafter, standard RSW) as the standard. In addition, comparison was also performed with 15 mm pitch RSW (hereafter, short pitch RSW), which is reported to have a high level of stiffness and strength⁽⁷⁾⁻⁽⁹⁾.

Figure 4 shows the bending test method. The entire circumference of the plate was welded to reduce hat part edge deformation during the bending test. The test conditions were three-point bending, indenter contact surface = R50, support jig contact surface = R30, and distance between supports = 700 mm. The indenter push-in amount was 200 mm, and the test speed was 10 mm/min.

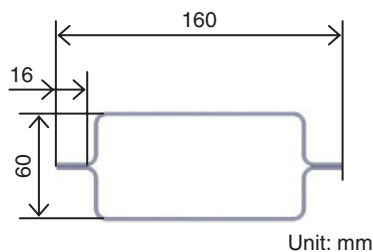


Fig. 2 Hat part section view

Table 1 Mechanical properties

	Measured value
Hardness (Hv)	494.3
Tensile strength (MPa)	1505.3
Yield strength (MPa)	1050.5
Elongation (%)	9.8

2.2. Test Results and Discussion

Figure 5 shows the test results. It was confirmed that weld fracturing did not occur for any test piece. Figure 6 shows the maximum reactive force and the absorbed energy. Compared to standard RSW, the absorbed energy was 1.5% higher for short pitch RSW, but was confirmed to be 5.5% lower for laser welding, 13.4% lower for arc

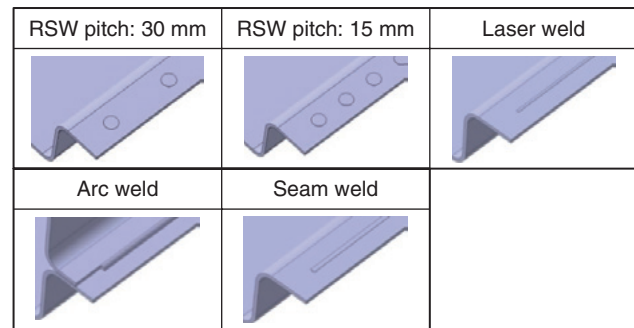


Fig. 3 Welding methods

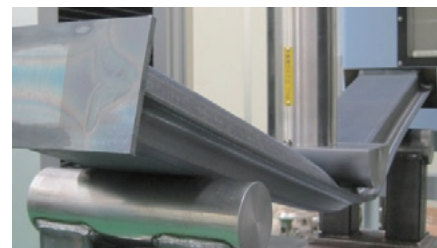
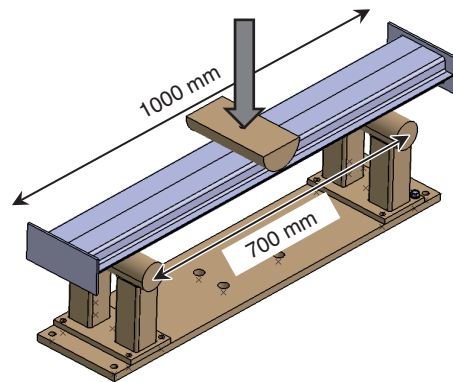


Fig. 4 Bending test specification

welding, and 7.0% lower for seam welding. This shows that the absorbed energy for continuous welding was lower than that for standard RSW in all cases.

The lower absorbed energy performance is presumed to be due to material softening as a result of the continuous welding heat. In addition, arc welding resulted in the lowest performance, which is thought to be because in addition to the heat effect, the joint is a lap fillet and the side to be welded has a short flange.

Hardness tests were performed in and around the areas melted by welding heat and then solidified by cooling to verify the material softening state. Figure 7 shows the results. The hardness of the base material before welding was approximately 500 Hv, and softening was confirmed to occur with each welding method. Standard RSW has a narrow softening range, and softening was confirmed over a wide range from the end of the flange, and including the hinge line areas for the continuous welding methods.

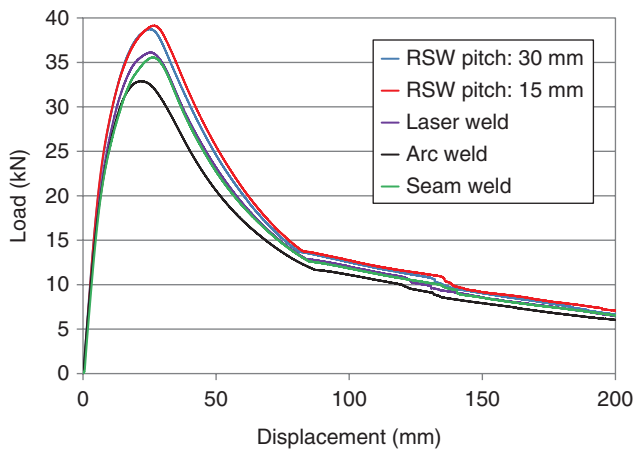


Fig. 5 Results of bending test

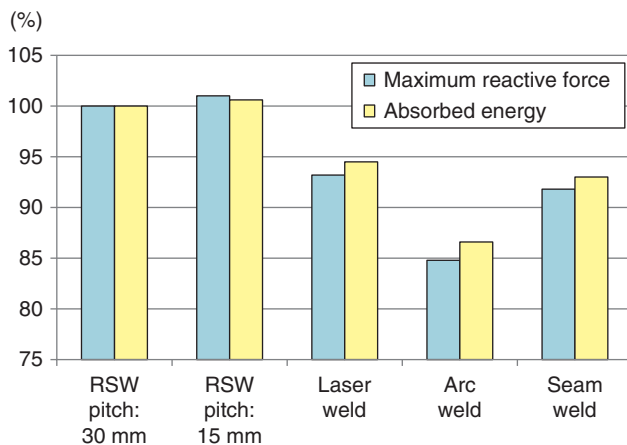


Fig. 6 Results of maximum reactive force and absorbed energy (compared to RSW pitch: 30 mm)

Therefore, specimens were cut from around the test piece welds and micro tensile tests were performed to clarify the tensile strength properties in the softening range. Figure 8 shows the specimen shape. Figure 9 shows the positions where the specimens were cut from the laser welded test piece, and Fig. 10 shows the test results. Reduced material strength compared to the base material was confirmed around the melt-solidified area and in the heat-affected zone.

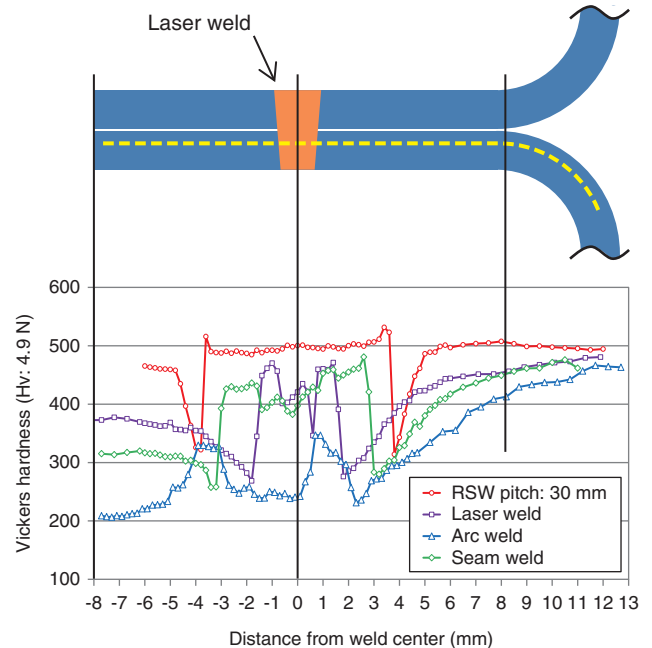


Fig. 7 Hardness test results

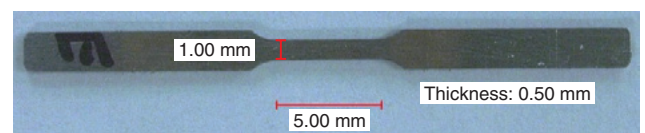


Fig. 8 Dimensions of micro specimen

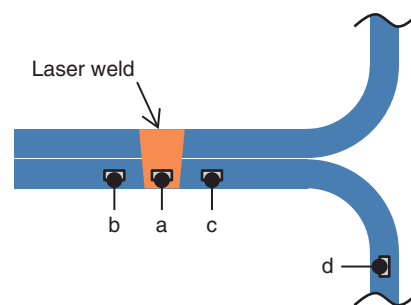


Fig. 9 Locations of micro specimens

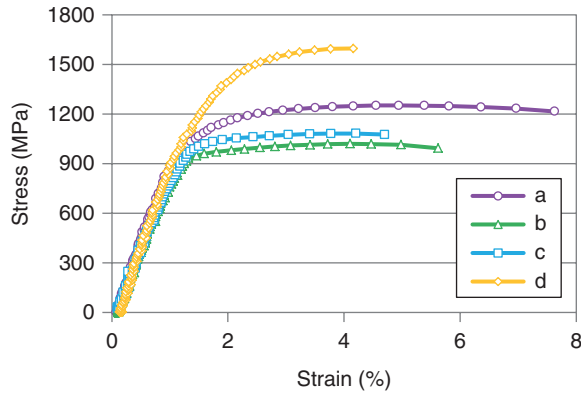


Fig. 10 Micro tensile test results (stress-strain curves)

3. Clarification of Mechanism Using CAE

The structure three-point bending test was modeled using structural analysis CAE to clarify the mechanism of reduced structure strength performance due to material softening by welding heat effect. Models were created for each of the five welding methods used to manufacture the test pieces, and verification was performed.

3.1. Analysis Model

First, the stress-strain curves of the plastic regions were modeled so that the micro tensile test results (Fig. 10) of the specimens cut from the test pieces could be used in structural analysis CAE. The yield stress was determined using 0.2% proof stress. A Young's modulus of 205.8 GPa and a Poisson's ratio of 0.3 were used.

Figure 11 shows the analysis model. This model expresses the hat part as a solid and the jigs as completely stiff surfaces. The boundary conditions all used a friction coefficient of zero. The structure was expressed using a square mesh with the sizes shown in Table 2. The mesh size is reduced in the 30 mm range, greatly deformed by contact with the indenter and the surrounding 75 mm range (Fig. 12).

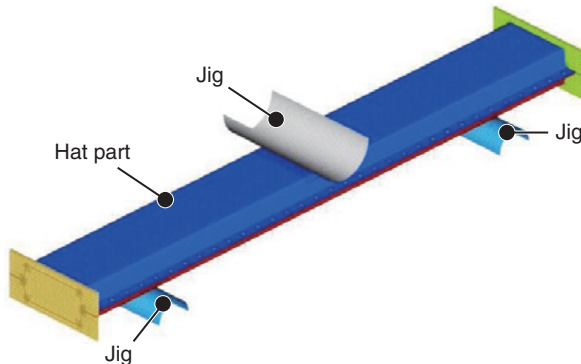


Fig. 11 CAE model

Table 2 Mesh size

		Unit: mm	
		Longitudinal direction	Lateral direction
Substrate	Low strain	3.75	5.12
	High strain	1.87	2.56
	Super-high strain	1.25	2.56
Joining area	Spot weld	3.00	
	Laser weld	3.75	0.50
	Arc weld	3.75	0.80
	Seam weld	3.75	0.80

Figure 13 shows the models of the structures made by using each welding method. Welding was reproduced by setting a 0.1 mm gap between the upper and lower hat part pieces and joining the welded areas across the gap.

Figure 14 shows the ranges where material softening was applied to the models for each welding method (hereafter, softening models). Modeling was performed with the softening range set based on the hardness test results (Fig. 7). The tensile strength values in each location used the values obtained from the micro tensile tests. For comparison of calculations, analysis was also performed using the same models without any softening locations (hereafter, non-softening models).

The ABAQUS explicit method was used as the solver.

3.2. CAE Analysis Results and Discussion

Figure 15 compares the results for the standard RSW test and the CAE model analysis. The results from load rise until the maximum reactive force is reached and the decreasing trend thereafter match closely, with a difference in absorbed energy of 1.6% or less.

Evaluation was performed using the absorbed energy for each welding method model to verify the softening model results. Figure 16 compares the results of tests using test pieces with the CAE results. The softening models

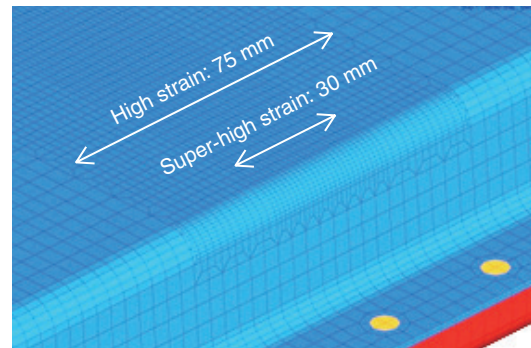


Fig. 12 CAE model detail

were confirmed to produce values close to the test values. In case of laser welding, the absorbed energy of the non-softening model was 7.7% higher than the test value, but the difference for the softening model was just 2.7%. In

	Joint shape	Joint width	Image
RSW pitch: 30 mm	Circular	ϕ 6 mm	
RSW pitch: 15 mm	Circular	ϕ 6 mm	
Laser weld	Rectangular	1.6 mm	
Arc weld	Quarter cylindrical	1.7 mm	
Seam weld	Rectangular	1.0 mm	

Fig. 13 Joint CAE models

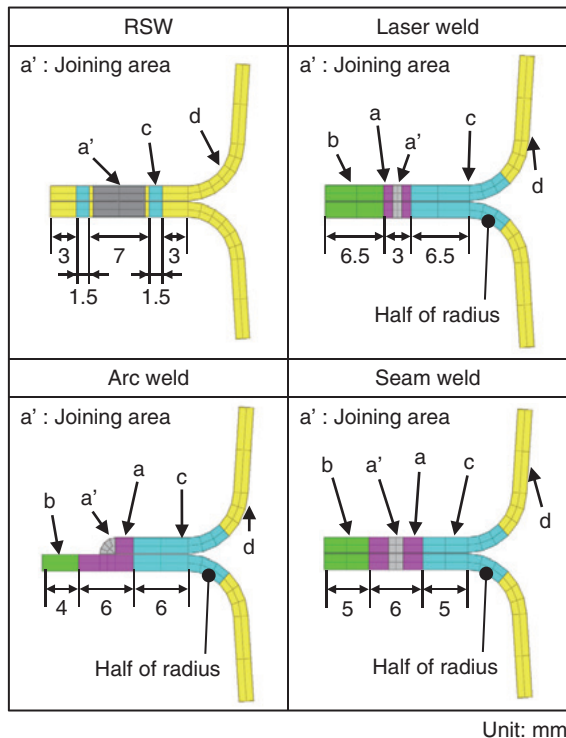


Fig. 14 CAE softening models

addition, the absorbed energy for short pitch RSW was higher than that for standard RSW, but was confirmed to correlate with the test values.

Figure 17 shows the stress distribution for a 100 mm stroke. The non-softening model in Fig. 17(a) exhibits high amounts of stress distributed widely around the welding flange. In contrast, the softening model in Fig. 17(b)

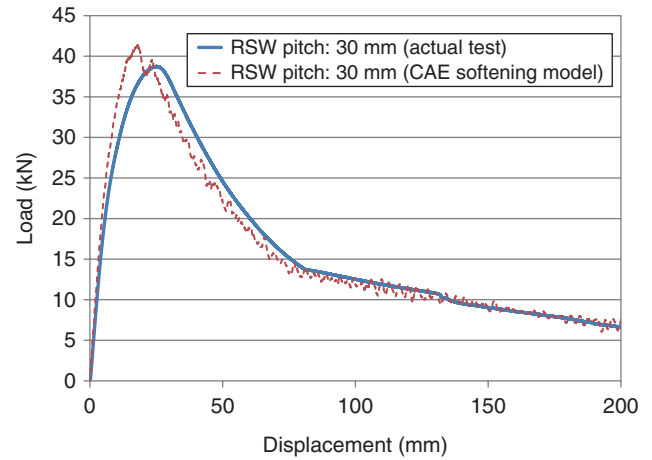


Fig. 15 Results of actual test and CAE softening model

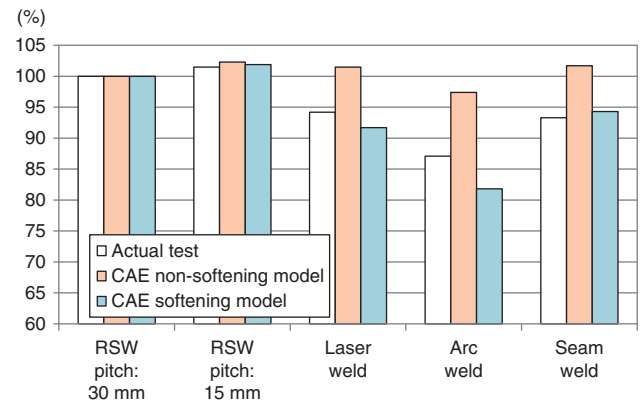


Fig. 16 Results of absorbed energy (compared to RSW pitch: 30 mm)

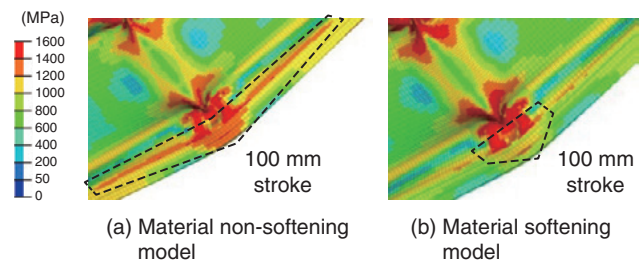


Fig. 17 Stress distribution

exhibits lower amounts of stress concentrated narrowly around the welding flange. This is because the plastic deformation around the welding flange proceeded under low stress. In this manner, stress concentrated around the indenter contact area in the condition with low stress around the welding flange, which resulted in lower absorbed energy.

These results clarified the mechanism of material softening by welding heat, resulting in lower reactive force and lower absorbed energy. In addition, this showed that structure strength performance can be predicted by modeling the strength properties for each heat-affected zone.

3.3. Clarification of Relationship between Softening Range and Structure Strength

Next, the effect of the softening range on the reduction of absorbed energy was investigated. The bending input does not produce a uniform stress distribution in the flange (welding location) and surrounding area as shown in Fig. 17. Therefore, the relationship between the material softening range and structure strength performance was investigated to identify the range over which heat-softening has a large strength performance reduction effect. The laser welding analysis model was used to create five different structure softening ranges for analysis, as shown in Fig. 18.

Model A is the non-softening model, and model B has softening in the outer half of the flange softened. Models C, D, and E have gradually wider softening areas as compared to model B.

Figure 19 shows the relationship between the softening area and the absorbed energy. The absorbed energy for condition C was just 2.4% less than that for the non-softening model A. However, when the hinge line area also softens such as in conditions D and E, the absorbed energy drops rapidly, and results were 9.4% lower for condition D, and 10.2% lower for condition E. The absorbed energy is almost the same for conditions D

and E, so it is thought that of the hinge line areas, much of the energy was absorbed by the flange corner part. Figure 20 shows the stress distributions for 50 mm and 100 mm strokes in condition A. At a stroke of 50 mm, the stress is widely distributed on the hinge lines around the indenter, and there is little stress on the flange part. At a stroke of 100 mm, the stress distribution is even wider in the hinge line areas, but there is little change in the flange area stress.

These results are thought to indicate that a softening of the hinge line areas that bear a large share of the stress had a large effect on the drop in absorbed energy. Therefore, it is thought that the drop in the energy absorbed by a structure can be reduced by suppressing softening of the hinge line areas.

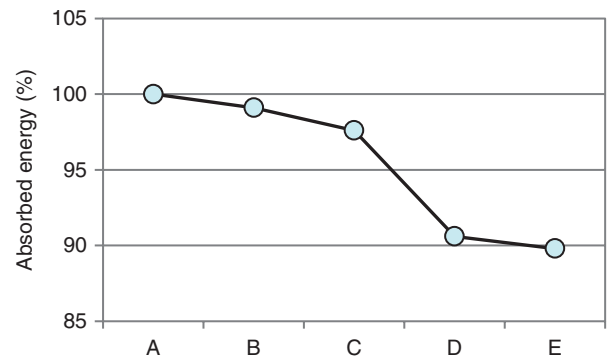


Fig. 19 Relationship between softening area and absorbed energy

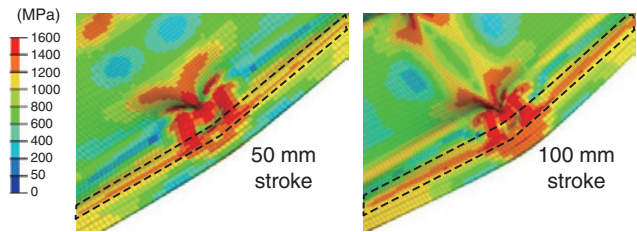


Fig. 20 Stress distribution at weld for condition A

Condition	A	B	C	D	E
Flange softening area	0%	50%	100%	100%	100%
Hinge line softening area	0%	0%	0%	50%	100%
CAE model					

Fig. 18 CAE softening model conditions

4. Development of Method for Suppressing Drop in Absorbed Energy

Tests using test pieces were performed to investigate the welding conditions in order to suppress heat softening of the hinge line areas. Faster welding speeds generally reduce the temperature rise around the weld. Therefore, increasing the laser welding speed was investigated. Simply increasing the speed lowers the welding quality, so the laser power was adjusted to achieve the same melting width. Table 3 shows the welding conditions. Condition 1 is the same condition

Table 3 Laser welding conditions

Condition	1	2	3
Welding speed (m/min)	1.0	2.5	8.0
Laser power (kW)	3	6	10

as in the previously investigated tests, and conditions 2 and 3 have faster welding speeds.

Figure 21 shows the bending test results. The absorbed energy was confirmed to rise for conditions 2 and 3, which have faster laser-welding speeds.

The surface temperatures of the hinge line areas were measured during welding to understand the heat transmission. Figure 22 shows the measuring point, and Fig. 23 shows the results. Compared to condition 1, the hinge line area was confirmed to have a lower temperature for conditions 2 and 3 with faster welding speeds. In addition, Fig. 24 shows the hardness test results around the weld location. This confirmed that the drop in hardness decreased and the range over which the hardness dropped was also narrower at lower temperatures.

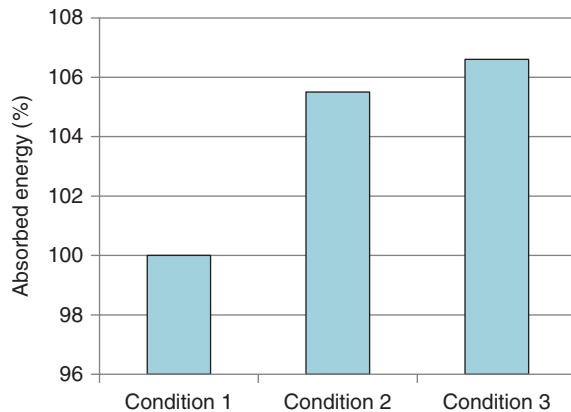


Fig. 21 Absorbed energy

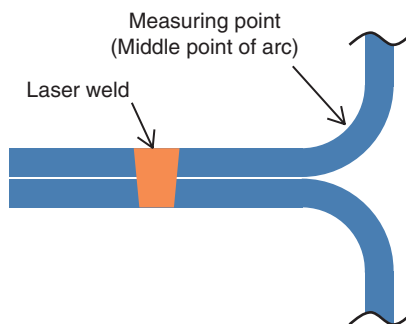


Fig. 22 Temperature measuring point

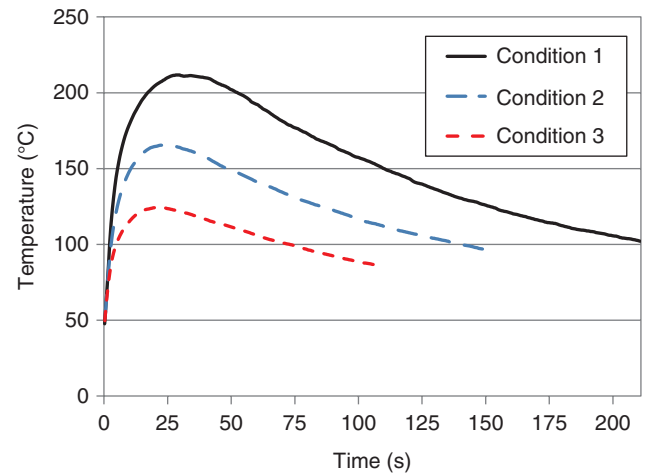


Fig. 23 Temperature history at middle point of arc

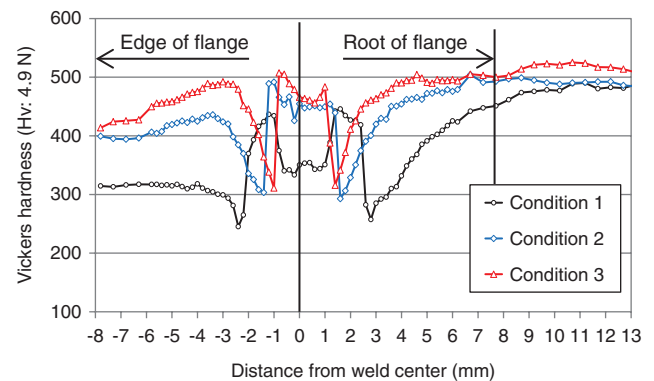


Fig. 24 Hardness test results of laser weld

5. Conclusion

The factors reducing strength due to welding heat in structures using hot-stamped materials was clarified, and the following conclusions were reached.

- (1) The mechanism of welding heat softening hot-stamped materials and resulting in lower absorbed energy was clarified.
- (2) CAE analysis was used to apply strengthening properties when material softening occurs to CAE models, which enabled prediction of structure strength performance.
- (3) Softening of the hinge line areas that bear a large share of the structural stress has a large reduction effect on structure strength performance.

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